

# Exploring the potential X-ray counterpart of the puzzling TeV gamma-ray source HESS J1507–622 with new *Suzaku* observations

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## ABSTRACT

The unidentified VHE ( $E > 100$  GeV) gamma-ray source HESS J1507–622 seems to not fit into standard models for sources related to young supernova remnants, pulsar wind nebulae, or young stellar populations in general. This is due to its intrinsically extended, but yet compact morphology, coupled with a relative large offset ( $\sim 3.5^\circ$ ) from the Galactic plane. Therefore, it has been suggested that this object may be the first representative of a new distinct class of extended off-plane gamma-ray sources. The distance to HESS J1507–622 is the key parameter to constrain the source’s most important properties, such as age and energetics of the relativistic particle population.

In this article we report on results of follow-up observations of the potential X-ray counterpart with *Suzaku*. We present detailed measurements of its spectral parameters and find a high absorbing hydrogen column density, compatible with the total amount of Galactic gas in this direction. In comparisons to measurements and models of the Galactic three-dimensional gas distribution we show that the potential X-ray counterpart of HESS J1507–622 may be located at the far end of the Galaxy. If the gamma-ray source is indeed physically connected to this extended X-ray source, this in turn would place the object outside of the usual distribution of Galactic VHE gamma-ray emitters.

**Key words:** cosmic rays - supernova remnants - neutron stars - gamma-rays: ISM - X-rays: ISM

## 1 INTRODUCTION

Multi-wavelength (MWL) observations are powerful tools to investigate the nature of unidentified very-high-energy (VHE,  $E > 100$  GeV) gamma-ray sources detected by ground-based imaging atmospheric Cherenkov telescopes such as H.E.S.S., VERITAS or MAGIC (for a review, see e.g. Hinton & Hofmann 2009). In particular, non-thermal X-ray sources are excellent observational tracers for highly energetic particles, and are in many cases linked to VHE gamma-ray sources. Prominent examples of such cases are the supernova remnants (SNRs) Tycho (Decourchelle et al. 2001) and RX J1713.7–3946 (Cassam-Chenaï et al. 2004) as well as pulsar wind nebulae (PWNe, for a review, see Gaensler & Slane 2006), such as MSH 15-52 (Trussoni et al. 1996). Two well-known Galactic VHE gamma-ray sources related to strong X-ray emitters are the PWNe HESS J1825–137 (Aharonian et al. 2005, 2006a) and Vela X (Aharonian et al. 2006b).

One, typically unknown, key quantity of unidentified gamma-ray sources is their distance. For Galactic sources, observations of their X-ray counterpart may help to constrain their location in the Galaxy. Soft X-rays are absorbed by atomic and molecular interstellar gas along the line of sight, and from the level of this attenuation the total column density (CD) of traversed gas (predominantly hydrogen) can be estimated (see e.g. Wilms et al. 2000). If the distribution of atomic and molecular hydrogen in the Galaxy is

known (e.g. Dickey & Lockman 1990; Ferrière 2001; Kalberla et al. 2005), constraints on the distance of the source can be placed, based on X-ray spectral measurements.

In the case where the level of soft X-ray attenuation is comparable to the total Galactic neutral hydrogen CD in this direction, the source is likely located at the far end or even outside of the Galaxy. This was the case for the VHE gamma-ray source HESS J1943+213, where the highly absorbed X-ray counterpart pointed towards an Extragalactic origin (Abramowski et al. 2011). For sources with a significant angular offset from the Galactic plane, this method can also be used to constrain their physical distance from the disk.

In observations performed by the H.E.S.S. array of imaging atmospheric Cherenkov telescopes an extended VHE gamma-ray source with an angular off-set of  $\sim 3.5^\circ$  from the Galactic plane was discovered (HESS J1507–622; Acero et al. 2011). This source features the second largest angular offset (next to the nearby SNR SN 1006) from the Galactic plane among all VHE gamma-ray sources that or not clearly linked to known Extragalactic objects. Despite detailed MWL analyses and theoretical considerations, the nature of this source has not been clearly identified yet. Interestingly, a faint, diffuse X-ray counterpart is likely connected to HESS J1507–622 (see sect. 2). The current literature favors a PWN interpretation for this object where the X-ray and VHE gamma-ray emission is produced by ultra-relativistic electrons through syn-

chrotron and inverse-Compton radiation, respectively (see sect. 4). However, the distance to HESS J1507–622, and its potentially associated X-ray nebula, is still unknown, but constitutes a key component for all attempts to model the evolution of the source as well as the radiation mechanisms.

In this article we present detailed spectroscopic results for this X-ray counterpart, based on newly available *Suzaku* observations, which can provide a direct estimate of the total CD of hydrogen ( $N_{\text{H}}$ ) in the line of sight towards this source and thus of its distance.

## 2 PREVIOUS X-RAY OBSERVATIONS WITH XMM-NEWTON AND CHANDRA

Following up on its original detection by H.E.S.S., the region around HESS J1507–622 has been observed once with *Chandra* (Acero et al. 2011) and twice with *XMM-Newton* (Tibolla et al. 2014).

In the 20 ks *Chandra* observation (ObsID: 9975) several point-like sources were detected but classified to be most likely unrelated to HESS J1507–622. This *Chandra* observation also revealed two extended sources. One of them (CXOU J150850.6–621018) is rather bright, with a flux of  $F_{\text{X}}(2\text{--}10\text{ keV}) = 7.0 \pm 0.7 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ , but outside of the intrinsic VHE gamma-ray size of HESS J1507–622 (Acero et al. 2011). As briefly outlined by Tibolla et al. (2014), assuming the X-ray source CXOU J150850.6–621018 and the VHE gamma-ray source HESS J1507–622 are physically related, the lack of overlap between the two would be hard to explain, even in an aged PWN scenario. For such an object, despite a much more extended IC/TeV nebula compared to the synchrotron/X-ray nebula, one still would expect IC emission from freshly injected electrons to overlap with the X-ray nebula, which is not seen when comparing CXOU J150850.6–621018 and HESS J1507–622. Prime examples for such aged PWN scenarios are HESS J1825–137 (Aharonian et al. 2005) and HESS J1303–631 (Aharonian et al. 2005), where the TeV sources are much more extended but still partly overlap with the more compact X-ray nebulae (see Uchiyama et al. (2009) and Abramowski et al. (2012), respectively). A link between HESS J1507–622 and the offset X-ray source CXOU J150850.6–621018 might thus require an even more evolved, relic PWN scenario.

The second extended X-ray source (CXOU J150706.0–621443) was detected with a statistical significance of  $\sim 7\sigma$  by *Chandra* and is spatially consistent with the VHE gamma-ray emission region. This source is rather faint, with a flux of  $F_{\text{X}}(2\text{--}10\text{ keV}) = 1.1^{+0.3}_{-0.5} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ , estimated from the *Chandra* count rate (Acero et al. 2011). Given the low flux, the limited statistics from the 20 ks *Chandra* observation did not allow for a detailed spectral study of CXOU J150706.0–621443. The extensions of the sources were estimated to be 20–25'' for CXOU J150706.0–621443 and 35–40'' for CXOU J150850.6–621018, respectively (Acero et al. 2011). Due to its positional coincidence and extended nature CXOU J150706.0–621443 was suggested as a potential counterpart to HESS J1507–622 (see Acero et al. 2011). To account for the very low X-ray flux compared to the flux in TeV gamma-rays, these authors suggested a relic PWN scenario with a very low magnetic field of  $\sim 0.5\mu\text{G}$ . Such a low magnetic field leads to a very faint X-ray nebula along with a large accumulation of highly energetic electrons radiating predominantly TeV gamma-rays via the IC mechanism.

**Table 1.** *Suzaku* observations

No.	sequence	exposure (ks)	Pointing position	
			R.A.	Dec.
1	507025010	79.8	15:06:56.6	–62:20:47
2	507026010	40.9	15:08:43.6	–62:09:52

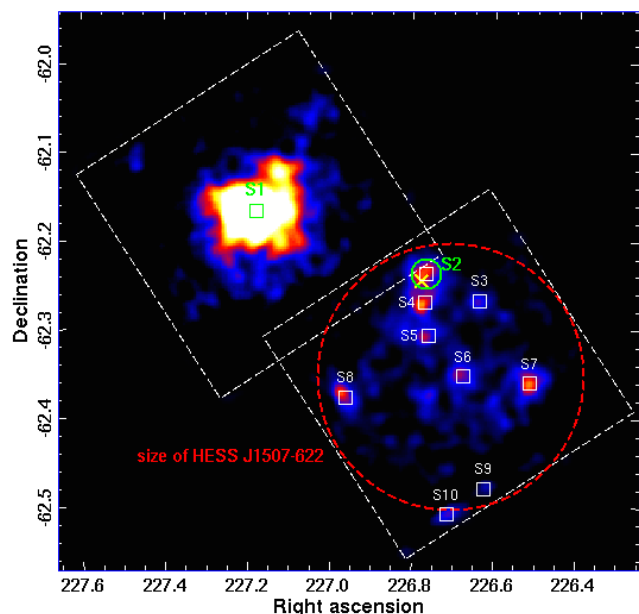
Unfortunately, both observations performed with *XMM-Newton* (ObsIDs: 0556310201, 0651620101) suffered from long periods of strong background flaring activity, rendering a significant fraction of the exposure time unusable for scientific analyses (see Acero et al. 2011; Tibolla et al. 2014). Even the remaining observation time of  $\lesssim 10$  ks featured an increased background level which affected the overall sensitivity, particularly for extended sources. However, both of the above mentioned extended *Chandra* sources were also detected in the second *XMM-Newton* observation (Tibolla et al. 2014). CXOU J150706.0–621443, the fainter of the two, was barely above the detection threshold with a statistical significance of  $\sim 4\sigma$ . Again, due to the limited number of counts no detailed spectral analysis was possible for CXOU J150706.0–621443. An additional source (XMMU J150835.7–621021; Tibolla et al. 2014), in close proximity (112'') to CXOU J150850.6–621018, was detected in the second *XMM-Newton* observation but not seen in the earlier *Chandra* data despite being above the detection threshold if assuming constant flux. Therefore, Tibolla et al. (2014) concluded that this source is probably variable and propose an X-ray binary or a flaring star as the most likely scenarios.

## 3 *Suzaku* DATA ANALYSIS

In September, 2012, the region of HESS J1507–622 was observed with *Suzaku* with two deep pointings, one of them (sequence No. 507025010, 79.8 ks) centered on HESS J1507–622 the other (sequence No. 507026010, 40.9 ks) centered on CXOU J150850.6–621018 (see Tab. 1 for more details). We analyzed the XIS data using the most recent versions of the HEADAS software package (v6.15.1; Blackburn 1995), and the HEASARC calibration database. We extracted images and spectra with *xselect* from the cleaned event lists using the recommended selection criteria (`STATUS<524287 && (STATUS%(2**17)<2**16)`) to remove events from the  $^{55}\text{Fe}$  calibration source.

We extracted count images from both front-illuminated detectors (XIS0 and XIS3) in the 1–10 keV energy range. To generate images of the contribution from the non-X-ray background (NXB) in this energy range we used the tool *xisnxbgen* (Tawa et al. 2008). After NXB subtraction we corrected the images for the mirror vignetting using a simulated exposure map created with the tool *xissim* (Ishisaki et al. 2009) at an energy of 2.5 keV. Fig. 1 shows a combined mosaic image of the two *Suzaku* observations.

To detect point-like and extended sources we used the *wavdetect* tool from the CIAO v4.6 software package (Fruscione et al. 2006), setting the chance probability for a false detection to 1%. The positions of all detected sources are listed in Tab. 2 and indicated by small squares in Fig. 1. The table also lists likely counterparts from previous *Chandra* and *XMM-Newton* observations (Acero et al. 2011; Tibolla et al. 2014). With the exception of two sources (Suzaku J1506.7–6221 and Suzaku J1506.5–6229)

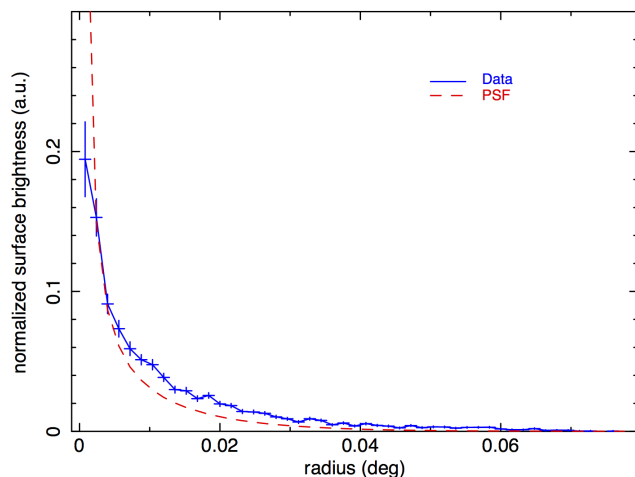


**Figure 1.** Combined mosaic of *Suzaku* XIS0 and XIS3 count maps from the two observations in the energy range 1–10 keV, smoothed with a Gaussian kernel with a width of 0.5. The dashed boxes (white) indicate the field of view of the two observations. The dashed circle (red) shows the position and intrinsic size of HESS J1507–622. The small boxes show the positions of sources detected with *wavdetect*. The cross (yellow) indicates the position of the faint diffuse source detected with *Chandra* and *XMM-Newton*, and the circle (green) shows the region used to extract the spectrum from CXOU J150706.0–621443. The color scale is linear and adjusted such that the fainter sources are visible, but S1 is highly saturated.

all detected objects have counterparts from previous X-ray observations (see Tab. 2). However, due to their low count rates, no more detailed analyses concerning their spectra or extensions are possible.

Due to the significantly larger PSF of *Suzaku* two previously detected X-ray sources fall within the range of Suzaku J1508.8–6210: The bright extended source CXOU J150850.6–621018 (Acero et al. 2011), also detected by *XMM-Newton* with consistent flux (XMMU J150851.1–621017; Tibolla et al. 2014), and the much fainter but variable source XMMU J150835.7–621021 (Tibolla et al. 2014, see also sect. 2). With *XMM-Newton* the flux of XMMU J150835.7–621021 was detected at  $\sim 10\%$  of the flux from CXOU J150850.6–621018. However, due to the apparent variability, the relative flux contributions may be different in this *Suzaku* observation (for further discussion see below). Due to this potential issue of source confusion, we will use the new *Suzaku* name for this source whenever we refer to the current analysis.

To test for an extension beyond the *Suzaku* PSF of Suzaku J1508.8–6210 we extracted its radial profile from the unsmoothed XIS0+3 counts image (1–10 keV). This profile is shown in Fig. 2 and compared to the on-axis PSF at an energy of 4.5 keV as stored in the *Suzaku* calibration database. To account for the diffuse astrophysical background component we subtracted from the data the surface flux level measured at offsets larger than  $0.07^\circ$  from the source position. The relative normalization between the data and PSF profiles was calculated such that they yield the same integral between 0 and  $0.06^\circ$ . As is evident from Fig. 2, the morphology of Suzaku J1508.8–6210 is incompatible with a point-like



**Figure 2.** Radial profile of Suzaku J1508.8–6210 (1–10 keV) from the XIS0+3 counts map (markers with error bars, blue), and the *Suzaku* PSF at 4.5 keV (dashed, red).

source, as already stated by Matsumoto et al. (2014) and Sakai (2013). However, due to the comparatively large PSF of *Suzaku*, it is unclear how much of this apparent extent is due to the intrinsic size of CXOU J150850.6–621018 or due to confusion with the off-set source XMMU J150835.7–621021 (see previous paragraph). Therefore, we suggest to refer to the extension measurements of CXOU J150850.6–621018 with *Chandra* (Acero et al. 2011) and *XMM-Newton* (Tibolla et al. 2014) for a more reliable estimate of this parameter.

Of particular interest here is the faint extended source CXOU J150706.0–621443, previously detected with *Chandra* and *XMM-Newton*, which can be also clearly identified in the new *Suzaku* observation: Suzaku J1507.0–6214. The position of Suzaku J1507.0–6214 is slightly shifted towards the North-West compared to the *Chandra* and *XMM-Newton* positions of CXOU J150706.0–621443 (see Acero et al. 2011; Tibolla et al. 2014), as indicated by the yellow cross in Fig. 1. However, the high-resolution *Chandra* results do not show any other source towards the shifted direction and we thus rule out source confusion due to *Suzaku*’s larger point spread function as the origin of the shift. More likely, the relative offset originates from uncertainties in the absolute pointing position of  $\sim 20''$  (see e.g. Uchiyama et al. 2008). We see similar offsets between the *Suzaku* and *Chandra* positions also for the other detected sources with *Chandra* counterparts in this observation. We therefore identify Suzaku J1507.0–6214 with CXOU J150706.0–621443 and use the original *Chandra* name for this object for all further discussion in this paper.

We extracted spectra from all sources which offered a sufficient number of counts (i.e. S1, S2, S4, S7, and S8) from all three detectors (XIS0, XIS1, XIS3). For all sources but Suzaku J1508.8–6210 we chose an extraction radius of  $60''$  which is recommended for point-like source analyses, and a nearby source-free region for the extraction of the background spectrum. Due to its intrinsic size and brightness we chose a larger radius of  $120''$  for Suzaku J1508.8–6210 and a large concentric annular region for the background (also see Tab. 2). These new deep *Suzaku* data offer the opportunity to study the spectrum of the faint extended source CXOU J150706.0–621443 which was not possible with previous observations by *Chandra* and *XMM-Newton* due to the limited count statistics.

**Table 2.** Detected sources

Source #	position		Source name Suzaku	radius <sup>(1)</sup> (")	background region <sup>(1)</sup>	X-ray counterpart <sup>(2)</sup>
	R.A.	Dec.				
S1	15:08:50.6	-62:10:18	J1508.8-6210	120	annulus: 260'' - 470''	CXOU J150850.6-621018 XMMU J150851.1-621017 XMMU J150835.7-621021
S2	15:07:04.9	-62:14:16	J1507.0-6214	60	offset, source-free region	CXOU J150706.0-621443
S3	15:06:35.9	-62:16:24	J1506.6-6216	-	-	CXOU J150636.9-621628
S4	15:07:08.2	-62:16:33	J1507.1-6216	60	offset, source-free region	CXOU J150708.8-621643 XMMU J150708.4-621642 CXOU J150706.7-621858
S5	15:07:06.0	-62:18:45	J1507.1-6218	-	-	-
S6	15:06:45.2	-62:21:30	J1506.7-6221	-	-	-
S7	15:06:06.3	-62:21:58	J1506.1-6221	60	offset, source-free region	CXOU J150606.7-622210
S8	15:07:54.0	-62:22:58	J1507.9-6222	60	offset, source-free region	CXOU J150756.0-622238 XMMU J150755.9-622237
S9	15:06:32.9	-62:29:07	J1506.5-6229	-	-	-
S10	15:06:54.5	-62:30:50	J1506.9-6230	-	-	CXOU J150656.1-623040

<sup>(1)</sup> Spectral extraction radius and description of background region in the case the statistics allowed for spectral fitting. <sup>(2)</sup> Likely counterpart from previous observations with *XMM-Newton* and *Chandra* (see Acero et al. 2011; Tibolla et al. 2014).

We performed the spectral fits with XSPEC v12 (Arnaud 1996) and used an absorbed powerlaw as well as a plasma (MEKAL) model to investigate both non-thermal and thermal radiation mechanisms. To model the photo-electric absorption we used the tbabs model along with the Galactic metal abundances from Wilms et al. (2000). For each source we fitted the spectra from all detectors simultaneously with linked spectral parameters. The spectral results are compiled in Tab. 3.

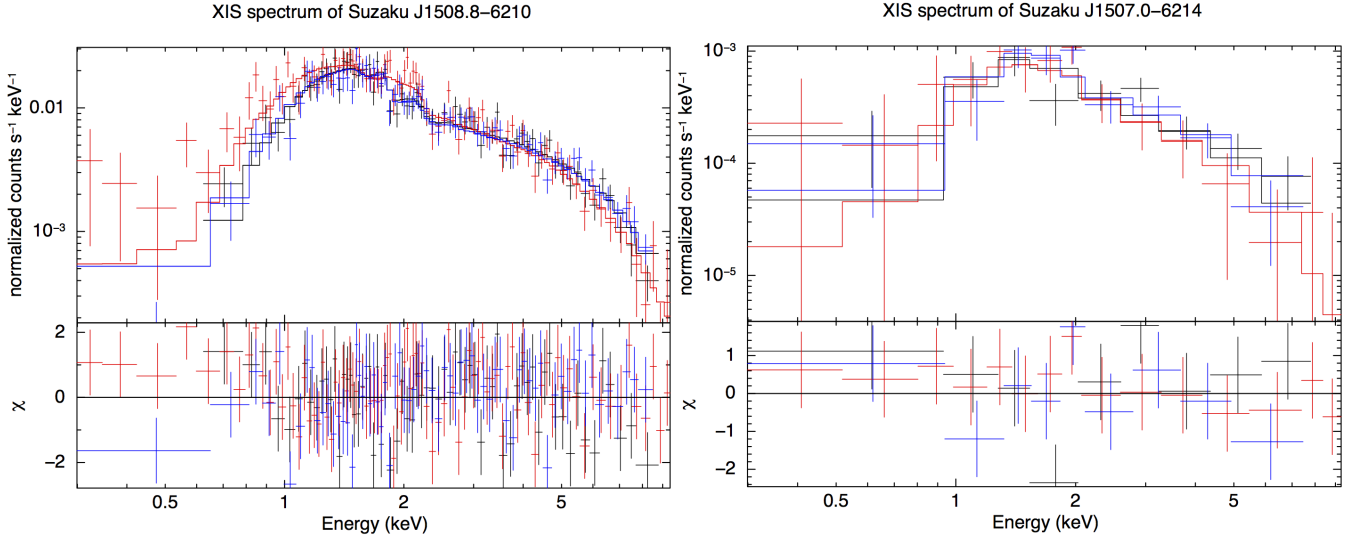
For four of these sources, flux estimates from previous X-ray observations with *XMM-Newton* and *Chandra* are available, three of them based on spectral fitting. For Suzaku J1507.9-6222 a previous flux estimate is available only from *XMM-Newton* where the flux was calculated from the count-rate assuming a certain spectral shape (see Tibolla et al. 2014, for details). Here, the new *Suzaku* flux is a factor of  $\sim 2$  lower compared to *XMM-Newton*, but still barely within the  $1\sigma$  statistical uncertainties. This discrepancy is probably due to differences between the assumed spectral parameters in the *XMM-Newton* measurement and the measured spectral shape in this work. Suzaku J1507.1-6216 has an *XMM-Newton* and *Chandra* counterpart with available spectral fitting results for *XMM-Newton* (see Tibolla et al. 2014). The fluxes are compatible within  $1\sigma$  uncertainties, however, the best-fit spectral slopes deviate significantly. This is most likely due to the fact that in the *XMM-Newton* analysis the absorption column density was fixed at the total Galactic value in this direction, whereas here we find that the source spectrum shows very little absorption with an upper limit on  $N_{\text{H}}$  well below the total Galactic value (see Tab. 3). Correlations between  $N_{\text{H}}$  and the spectral slope likely explain the discrepancies in spectral index.

Below, we discuss the results for the two extended sources Suzaku J1508.8-6210 and CXOU J150706.0-621443 in more detail. Figure 3 shows the spectra for these two sources along with the best-fit powerlaw models. Judging from the  $\chi^2$  values, the powerlaw model is clearly preferred for Suzaku J1508.8-6210 ( $\geq 5\sigma$ ), whereas there is no clear preference for CXOU J150706.0-621443, given the current data. For both sources, the value of  $N_{\text{H}}$  appears to be large (see discussion in sect. 4.2) and, in the case of Suzaku J1507.0-6214, rather independent of the assumed spectral shape.

Matsumoto et al. (2014) and Sakai (2013) already reported

about results for these two extended sources based on the same *Suzaku* dataset. These authors confirmed the extended nature of Suzaku J1508.8-6210. However, the lower count statistics from CXOU J150706.0-621443, coupled with its more compact size, make it point-like for *Suzaku*. Our spectral results are compatible in terms of photon index and flux with the ones obtained by the authors above. However, we find systematically larger values for the hydrogen column density  $N_{\text{H}}$ . Unfortunately, the description of the spectral analysis by these authors is not complete, and key information like the used absorption model and the assumed metal abundances are missing. We were able to reproduce the results of Matsumoto et al. (2014) and Sakai (2013) by changing from Galactic to solar metal abundances. Because of the higher metallicity of the sun compared to the average Galactic level, a lower equivalent hydrogen CD is needed for the same absorption effect, thus the lower  $N_{\text{H}}$  value in their fit. However, because these sources are very likely of extra-solar origin, we remain with Galactic abundances and deem our results to be more realistic.

As already discussed in the first paragraph of this section, Suzaku J1508.8-6210 may be composed of the two independent X-ray sources CXOU J150850.6-621018 and XMMU J150835.7-621021. To compare with the previous *Chandra* result (Acero et al. 2011) we calculated a flux of Suzaku J1508.8-6210 in the 2-10 keV band of  $(9.8 \pm 0.3) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$  which is about 30% higher than the *Chandra* measurement of CXOU J150850.6-621018. This difference might arise from an additional contribution from the fainter but variable source XMMU J150835.7-621021. In this case the latter source must have had a  $\sim 3$  times higher flux during the *Suzaku* observation than during the earlier *XMM-Newton* measurement (see Tibolla et al. 2014). Variability of this magnitude is very well plausible for flaring stars (see, e.g. Liefke et al. 2010) and X-ray binaries (for a review, see van den Berg 2010), the two most plausible scenarios for XMMU J150835.7-621021 as suggested by Tibolla et al. (2014). Another contributing factor to the larger flux seen with *Suzaku* from Suzaku J1508.8-6210 compared to *Chandra* and *XMM-Newton* could arise from the larger region used for spectral extraction. However, this would only be the case if CXOU J150850.6-621018 is much more extended



**Figure 3.** *Suzaku* spectra of the two extended sources Suzaku J1508.8–6210 (left) and CXOU J150706.0–621443 (right) shown together with the best-fit absorbed powerlaw model (stepped lines). The colors indicate the spectra from the individual cameras: XIS-0 (black), XIS-1 (red), XIS-3 (blue).

**Table 3.** X-ray spectral fitting results

source	$N_{\text{H}}^{(1)}$ ( $10^{21} \text{ cm}^{-2}$ )	$\Gamma / kT^{(2)}$ (-)/(keV)	$F_{\text{obs}}^{(3)}$ ( $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ )	$F_{\text{unabs}}^{(4)}$	$\chi^2 / \text{ndf}$
<i>powerlaw</i>					
S1	$7.4^{+1.0}_{-1.0}$	$1.83^{+0.08}_{-0.08}$	$11.9^{+0.3}_{-0.2}$	$13.8^{+0.5}_{-0.5}$	222.19 / 223
S2	$11.7^{+8.8}_{-6.5}$	$2.2^{+0.6}_{-0.5}$	$0.89^{+0.14}_{-0.12}$	$1.6^{+0.3}_{-0.3}$	23.93 / 30
S4	$<1.7$	$2.5^{+0.6}_{-0.4}$	$0.55^{+0.09}_{-0.08}$	$0.58^{+0.12}_{-0.10}$	52.1 / 50
S7	$26^{+27}_{-15}$	$2.0^{+0.9}_{-0.7}$	$1.1^{+0.1}_{-0.1}$	$2.1^{+1.0}_{-0.9}$	54.7 / 45
S8	$<15$	$1.7^{+0.9}_{-0.8}$	$1.0^{+0.4}_{-0.3}$	$1.4^{+0.9}_{-0.7}$	30.4 / 38
<i>MEKAL</i>					
S1	$4.7^{+0.6}_{-0.6}$	$8.5^{+1.4}_{-1.5}$	$11.8^{+0.4}_{-0.3}$	$12.9^{+0.4}_{-0.4}$	266.81 / 223
S2	$11.4^{+7.5}_{-6.7}$	$3.3^{+3.7}_{-1.2}$	$1.0^{+0.3}_{-0.2}$	$1.5^{+0.3}_{-0.3}$	23.48 / 30
S4	$<0.7$	$2.8^{+1.2}_{-0.7}$	$0.57^{+0.6}_{-0.07}$	$0.58^{+0.13}_{-0.12}$	59.8 / 50
S7	$25^{+23}_{-14}$	$4.6^{+8.0}_{-2.2}$	$1.1^{+0.3}_{-0.2}$	$1.8^{+0.7}_{-0.5}$	54.4 / 45
S8	$11^{+11}_{-9}$	$6.5^{+25}_{-3.7}$	$1.0^{+0.4}_{-0.2}$	$1.3^{+0.7}_{-0.6}$	29.7 / 38

all quoted uncertainties are at 68% confidence, and calculated with all other model fit parameters free to vary; <sup>(1)</sup>absorbing hydrogen column density (CD); <sup>(2)</sup>photon index or plasma temperature, depending on the assumed model; <sup>(3)</sup>observed energy flux (1–10 keV); <sup>(4)</sup>unabsorbed energy flux (1–10 keV), with the effects of foreground absorption removed

than estimated from the *XMM-Newton* and *Chandra* maps, with a surface flux in the tails below their detection limit.

## 4 DISCUSSION

Out of the two extended X-ray sources in the vicinity of HESS J1507–622, originally detected by *Chandra*, in the following discussion we deem CXOU J150706.0–621443 to be the more likely counterpart to the TeV emission due to its spatial coincidence with the intrinsic size of HESS J1507–622, which is not the case for CXOU J150850.6–621018 (Suzaku J1508.8–6210). Due to the lack of overlap with the VHE gamma-ray size of HESS J1507–622,

the latter source was considered a less likely counterpart in a PWN scenario (see Acero et al. 2011; Tibolla et al. 2014, and also Sect. 2).

After the discovery of HESS J1507–622, a leptonic scenario was favored (Acero et al. 2011) while hadronic scenarios were considered unlikely (Domainko 2011). Acero et al. (2013) reported a point-like *Fermi-LAT* counterpart with soft spectrum. However, the nature of the source still remains elusive. On the one hand, several PWN models were successfully applied to describe the emission seen from HESS J1507–622: Tibolla et al. (2011) proposed an ancient PWN model (developed by de Jager et al. 2009), Tibolla et al. (2012) fitted a modified leaky-box model (Zhang et al. 2008), and Vorster et al. (2013) managed to describe HESS J1507–622 with a time-dependent PWN model. On the other hand, no pulsar has been detected in the vicinity of HESS J1507–622 (Acero et al. 2011).

The nature of the TeV gamma-ray source HESS J1507–622 is challenging to explain with established models for Galactic sources, such as young supernova remnants and PWNe, due to its large offset from the Galactic plane coupled with its apparent compactness. In a PWN scenario the latter feature may indicate either that the source is nearby and still young, or that the source is more evolved and far away. The problems with the first scenario are the absence of a young ( $\lesssim 10^4$  yr) and powerful pulsar and the relatively low X-ray flux of the candidate synchrotron nebula CXOU J150706.0–621443. To explain the low X-ray flux, in the second scenario the PWN would be a more evolved system (e.g. Mattana et al. 2009; Balbo et al. 2010). In this framework Acero et al. (2011) found a distance of HESS J1507–622 of  $>6$  kpc by comparing its angular extent with the size of the nearby, evolved Geminga PWN. A distance of 6 kpc has also been adopted in previous PWN models (Tibolla et al. 2011; Tibolla et al. 2012; Vorster et al. 2013). If the extension of HESS J1507–622 is driven by diffusion of energetic electrons for a time-scale of  $2 \times 10^4$  years, the distance to the object needs to be very large ( $\gtrsim 10$  kpc) to be compatible with the apparent compactness of the TeV source (Domainko & Ohm 2012). This in turn implies a large physical distance of HESS J1507–622 from the Galactic plane, in particular much

larger than the scale height of the distribution of VHE gamma-ray emitting pulsars. A remedy for this situation would be an association to hyper-velocity stars or HESS J1507–622 being a member of a new population of gamma-ray sources associated to older stellar populations. For a more detailed discussion of these scenarios see Domainko & Ohm (2012) and Domainko (2014).

As becomes evident from the above discussion, the most important, but yet unknown parameter is the distance of HESS J1507–622 from Earth. Also, the details of the spectral shape and the flux of the non-thermal X-ray counterpart to HESS J1507–622 are very valuable to constrain intrinsic source properties, such as magnetic field and age.

In the subsections below we explore the implications of the measured spectral parameters of CXOU J150706.0–621443 on its distance (using  $N_H$ ), and on the properties of the underlying relativistic particle population (using the spectral index and flux).

#### 4.1 Modeling the spectral energy distribution

We use our spectral measurement of CXOU J150706.0–621443 for an updated modeling of the spectral energy distribution (SED) of HESS J1507–622. We assume that CXOU J150706.0–621443 is physically related to HESS J1507–622 because of its extended nature and its spatial coincidence with the VHE gamma-ray source. Fig. 4 shows the broad-band spectral measurements used for this study. Here, the X-ray data points are the unfolded (corrected for instrument response) data from the *Suzaku* observation, corrected for the foreground absorption as determined by the best-fit power-law model, taking also parameter uncertainties into account (hence the large error bars of the lowest energy data point where the influence of  $N_H$  is strongest). In addition to the new *Suzaku* spectral data points of CXOU J150706.0–621443 we show in Fig. 4 also the uncertainty range of the previous best-fit powerlaw model measured with *Chandra* (see Tibolla et al. 2014). The latter is only an approximation, calculated from the quoted uncertainties of the integral flux and photon index, assuming no parameter correlations (as the full covariance matrix of the *Chandra* fit has not been published). The uncertainties of the *Chandra* measurement are very large due to limited statistics and both spectra are compatible within errors. The slightly lower flux seen with *Chandra* may arise from the smaller size of the spectral extraction region compared to the new *Suzaku* analysis.

A case for a leptonic origin of HESS J1507–622 has been made in the past by various authors (Acero et al. 2011; Tibolla et al. 2011; Tibolla et al. 2012; Vorster et al. 2013) in the framework of a PWN scenario (see also Weiler & Panagia 1978; Gaensler & Slane 2006). One-component broken powerlaw electron spectra (Torres et al. 2014) and two-component electron spectra (Vorster et al. 2013) were adopted to fit the SED of several PWNe. For HESS J1507–622, using the flux measurement from the 2-year *Fermi-LAT* source catalog (2FGL) below 100 GeV (Nolan et al. 2012), Vorster et al. (2013) were able to fit the SED of HESS J1507–622 with a two-component electron spectrum. Here, we adopt the result of the longer 34-month *Fermi-LAT* data set analyzed by (Domainko & Ohm 2012) for energies below 100 GeV, following the approach of Torres et al. (2014), and fit a one-component electron spectrum. This is mainly done to reduce the number of free parameters compared to a two-component injection spectrum.

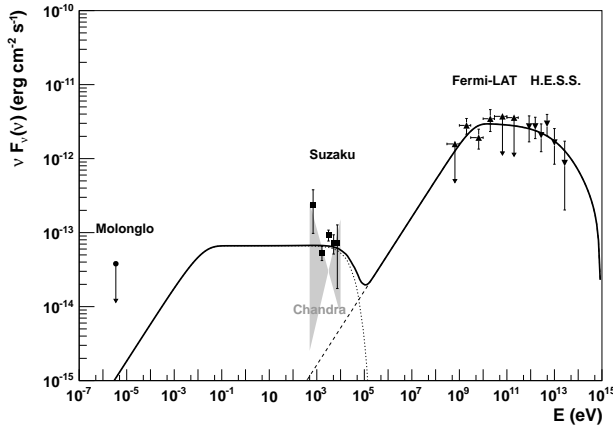
We assume a broken powerlaw energy distribution for the radiating electrons with a spectral break of  $\Delta\Gamma = 1$ , as expected for a cooling break for continuous injection over longer periods of time

caused by synchrotron and inverse-Compton radiation in the Thomson regime. With these assumptions we find a best-fit model with a spectral index below the break energy ( $E < E_{\text{break}}$ ) of  $\Gamma = 2$ , for  $E > E_{\text{break}}$  a spectral index of  $\Gamma = 3$ , and  $E_{\text{break}} = 0.9$  TeV. The total energy in electrons is  $5 \times 10^{47} (d/1 \text{ kpc})^2$  erg with  $d$  being the distance to the source. The maximum energy of electrons in this model is  $E_{\text{max}} = 1$  PeV, a value which is necessary to reproduce the highest energy X-ray data points.

From this model fit, constraints on the age of the radiating electrons can be obtained. For the case where the break at 0.9 TeV in the broken powerlaw is introduced by inverse-Compton cooling on the CMB, this would point towards an age of the source of  $\approx 10^6$  years, i.e. a rather old source. This can be compared to age estimates based on the evolution of PWNe if such an origin is adopted for HESS J1507–622. Mattana et al. (2009) found that the ratio of the flux in VHE gamma-rays (1–10 TeV)  $F_\gamma$  and the flux in X-rays (2–10 keV)  $F_X$  strongly increases with PWN age. Applying this method for HESS J1507–622 with  $\log(F_\gamma/F_X) \approx 1.85$ , an age of about  $3 \times 10^4$  years and thus a rather evolved PWN would be found. This is consistent with the fact that the size of the TeV source is much larger than the size of the X-ray source for evolved PWN (Kargaltsev & Pavlov 2010) which also appears to be the case for HESS J1507–622. An age of about  $3 \times 10^4$  years would be in line with the PWN models of Tibolla et al. (2012) and Vorster et al. (2013). This age estimate is significantly smaller than the age of the Geminga PWN. Therefore, in the PWN scenario, HESS J1507–622 could be significantly less extended than the Geminga PWN and could thus be located closer than the 6 kpc as discussed above (note that the multi-kpc distance estimate in Sect. 4.4 is independent from spectral modelling and only based on the X-ray absorption measurement of the potential X-ray counterpart). The caveat for this interpretation is the smaller  $F_\gamma/F_X$  ratio of Geminga with respect to HESS J1507–622. Vorster et al. (2013) proposed the passage of the reverse shock to resolve this discrepancy. In this paper we did not consider the effect of a past reverse shock passage on HESS J1507–622. Our modelling parameters are given for the present particle spectrum in this source. It has also to be noted that no supernova remnant has been detected around HESS J1507–622. Additional constraints on the age of radiating electrons can be placed by the maximum particle energy. Electrons with an energy of about 1 PeV cool very fast via inverse-Compton radiation, and have to have been injected less than 1 kyr ago into the system. This may indicate the presence of a second spectral component at the highest energies and more generally may indicate that a two-component electron spectrum seems to be favored over a one-component electron spectrum. To summarize, for a leptonic scenario the SED of HESS J1507–622 suggests a rather evolved system albeit with recent injection of highly energetic particles.

In this model the magnetic field  $B$  is  $0.47 \mu\text{G}$ . This value for  $B$  is consistent with the estimates of by (Acero et al. 2011) but is smaller than the values found by (Domainko & Ohm 2012,  $1 \mu\text{G}$ ) and (Vorster et al. 2013,  $1.7 \mu\text{G}$ ). The reason for this difference is the fact that here the measured hard X-ray spectrum for CXOU J150706.0–621443 is used for the SED modeling, in contrast to the softer spectra assumed in the previous studies.

One caveat of such leptonic one-zone models is the significant difference of sizes of the emission regions in the X-ray and gamma-ray regimes. This may introduce a bias (i.e. underestimation of the synchrotron flux) in models where it is assumed that the X-ray and TeV fluxes are produced by the same population of electrons. With *Chandra* the size of CXOU J150706.0–621443 was estimated to be 20–25'' (Acero et al. 2011), and with the new *Suzaku* data the



**Figure 4.** Broad-band SED of HESS J1507–622, including the Radio flux upper limit from Molonglo (Domainko & Ohm 2012; Bock et al. 1999), the uncertainty band of the best-fit powerlaw spectrum measured with *Chandra* (shaded area, Tibolla et al. 2014), the *Suzaku* data points for CXOU J150706.0–621443 from this work, Fermi measurements in the high-energy gamma-ray regime (Domainko & Ohm 2012) and H.E.S.S. flux points at energies larger than 100 GeV (Acero et al. 2011). Additionally, the model SED is shown, assuming Synchrotron (dots) and IC emission (dashes) from a broken powerlaw electron distribution. See sect. 4.1 for a detailed description of the model.

associated source (Suzaku J1507.0–6214) appears to be point-like and its flux to be contained within a radius of  $\sim 60''$  (which is also the suggested spectral extraction radius for point-like sources with *Suzaku*, see also Fig. 1).

However, a larger scale emission component comparable to the intrinsic size of HESS J1507–622 may not be detectable if the surface flux in X-rays is sufficiently low. For a very conservative estimate of the highest possible X-ray flux from the TeV emission region, we use the ratio between the intrinsic size of HESS J1507–622 and the area used for spectral extraction from CXOU J150706.0–621443 in this work ( $\rho_{\text{area}} = (A_{\text{TeV}}/A_{\text{X-ray}}) \approx 80$ ), as well as the ratio of the X-ray surface flux from source-free regions and the region of CXOU J150706.0–621443 ( $\rho_{\text{flux}} = (F_{\text{source-free}}^{\text{surf}}/F_{\text{Suzaku J1507.0-6214}}^{\text{surf}}) \approx 0.33$ ). Assuming that all the diffuse X-ray surface flux from source-free regions is related to HESS J1507–622 a scaling factor of  $\rho_{\text{area}} \cdot \rho_{\text{flux}} \approx 27$  needs to be applied to the measured flux from CXOU J150706.0–621443. The implications of the increased X-ray flux on the model parameters would be an enhanced magnetic field (by a factor of  $\sqrt{27} \approx 5$ , i.e.  $B \approx 2.9 \mu\text{G}$ ) and a cut-off of the electron spectrum decreased by the same factor, i.e.  $E_{\text{max}} \approx 200 \text{ TeV}$  (following Hinton & Hofmann 2009).

## 4.2 Comparison to measured values of the neutral hydrogen column

The values of  $N_{\text{H}}$  derived from the X-ray spectra in sect. 3 can be compared to measured values of the total absorbing CD of neutral hydrogen in the direction of the sources. Soft X-rays are absorbed by interstellar gas, which predominantly consists of atomic (HI) and molecular hydrogen ( $\text{H}_2$ ).

The HI distribution in the galaxy has been measured by Dickey & Lockman (1990) and Kalberla et al. (2005). For the direction of HESS J1507–622 Dickey & Lockman (1990) esti-

mated a HI CD of  $5.0 \times 10^{21} \text{ cm}^{-2}$  and Kalberla et al. (2005) constrained it to  $4.2 \times 10^{21} \text{ cm}^{-2}$ . In comparison to these values Suzaku J1508.8–6210 and CXOU J150706.0–621443 seem to be absorbed on a comparable or even higher level. This indicates that these sources are located at the edge or even outside the main HI distribution of the Galaxy. The excess absorption for the two sources in comparison to the values found in the surveys could in principle be attributed to Galactic molecular hydrogen that is not measured in the HI surveys.

Absorption by neutral hydrogen in soft X-rays is tightly correlated to dust absorption in the optical (Predehl & Schmitt 1995). Consequently, from the measured level of dust absorption ( $A_{\text{V}}$ ), the total CD in cold hydrogen can be estimated. For CXOU J150706.0–621443 (located inside HESS J1507–622) we find  $A_{\text{V}} = 4.6$  and for Suzaku J1508.8–6210  $A_{\text{V}} = 3.7$  (Schlafly & Finkbeiner 2011)<sup>2</sup>. These measured values of  $A_{\text{V}}$  correspond to a cold hydrogen absorption of  $8.2 \times 10^{21} \text{ cm}^{-2}$  for CXOU J150706.0–621443 and  $6.6 \times 10^{21} \text{ cm}^{-2}$  for Suzaku J1508.8–6210 (Predehl & Schmitt 1995). These comparisons evidence that both sources experience soft X-ray absorptions consistent with the total Galactic CD of neutral hydrogen. However, it has to be noted that the measurement of dust absorption may not be precise at Galactic latitudes  $< 5^\circ$  (Schlafly & Finkbeiner 2011).

An alternative method to determine the total X-ray absorbing hydrogen CD is described by Willingale et al. (2013) who used 493 gamma-ray burst afterglows to calibrate estimates of  $N_{\text{H}}$  based on measurements of atomic hydrogen and dust extinction. Using their web tool<sup>3</sup> to estimate the total ( $N_{\text{HI}} + N_{\text{H}_2}$ ) for the region of HESS J1507–622 we get a value of  $N_{\text{H}} \approx 5.7 \cdot 10^{21} \text{ cm}^{-2}$  and for Suzaku J1508.8–6210 we obtain  $N_{\text{H}} \approx 5.9 \cdot 10^{21} \text{ cm}^{-2}$ . Both values are slightly lower than estimated from the dust absorption  $A_{\text{V}}$  directly (see previous paragraph).

## 4.3 Comparisons to models of the Galactic neutral hydrogen distribution

The highly absorbed X-ray spectrum of CXOU J150706.0–621443 may suggest that any associated object is located at a considerably large distance to Earth. In order to estimate the source distance, we use a large-scale 3D model for both atomic and molecular Galactic hydrogen gas and compare it to the CD derived from the *Suzaku* measurements. This model is based on the descriptions of the large-scale distribution of HI and  $\text{H}_2$  gas in the Milky Way by various authors, summarized by Ferrière (2001). There, a galacto-centric distance of the sun of  $R_\odot = 8.5 \text{ kpc}$  is assumed, and gas distributions that apply different values of  $R_\odot$  are rescaled to the updated value by the author. We also adopt this value of  $R_\odot$  in the following.

The large-scale distribution of each of the mentioned gas components is modeled as follows: First, the radial (i.e. with  $R$ , the distance to the Galactic center along the Galactic plane) distribution of the azimuth averaged gas CD *perpendicular* to the Galactic plane (vertical CD) is obtained. Second, the radial profile of the gas layer thickness is determined. Lastly, a vertical density distribution function is assumed, and its normalization and width is determined by the two other distributions. As a result, for each set of coordinates  $\{R, z\}$ , where  $z$  is the vertical distance to the Galactic plane, a space-averaged number density of hydrogen nuclei can be calculated.

<sup>1</sup> <http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl>

<sup>2</sup> <http://ned.ipac.caltech.edu/>

<sup>3</sup> <http://www.swift.ac.uk/analysis/nhtot/index.php>



Furthermore, we allow for a large-scale Galactic spiral arm structure by modulating the gas densities towards the arms in a simple manner, as described in sect. 4.3.3.

#### 4.3.1 Atomic hydrogen (HI)

Dickey & Lockman (1990) provide the azimuth averaged radial distribution of the HI vertical CD, which can be roughly described by a three-component structure: a depletion at the Galactic center followed by an increase to a value of  $6.2 \times 10^{20} \text{cm}^{-2}$  at a distance of  $R = 3.5 \text{ kpc}$  (region (i)). This transitions into a constant regime (region (ii)) which passes through the solar circle and out to almost  $R = 14 \text{ kpc}$ . At farther distances (region (iii)), the values of the vertical CD again decrease in an exponential fashion. We use the following parameterization to describe the radial distribution of the vertical HI CD:

$$\text{CD}_{\text{HI}} = (6.2 \cdot 10^{20} \text{cm}^{-2}) \begin{cases} \exp\{-(R-3.5)/0.7\}^2 & \text{(i)} \\ 1 & \text{(ii)} \\ \exp\{-(R-13.65)/3.57\} & \text{(iii),} \end{cases}$$

with  $R$  in units of kpc.

The HI gas layer thickness is modeled according to Dickey & Lockman (1990): The FWHM increases from the Galactic center outwards to  $R = 3.5 \text{ kpc}$  (region (a)) from 165 pc to 230 pc. Between  $R = 3.5 \text{ kpc}$  and the solar circle (region (b)) the layer thickness is assumed to remain constant at a value of 230 pc. We model the flaring of the gas layer outside the solar circle (region (c)) by a linear increase to a value of about 3 kpc at  $R = 25 \text{ kpc}$ .

$$\text{FWHM}_{\text{HI}} = (1 \text{ kpc}) \begin{cases} 0.065 \exp\{-(R-3.5)/7.1\} + 0.165 & \text{(a)} \\ 0.23 & \text{(b)} \\ 0.154 \cdot (R-8.5) + 0.23 & \text{(c)} \end{cases}$$

Finally, we use the vertical density profile reported by Ferrière (2001), resembling two Gaussian functions plus an exponential tail:

$$\langle n_{\text{HI}} \rangle(R, z) = k(R) \left[ 0.7 \cdot \exp\left\{-\left(\frac{z}{0.55 \cdot \text{FWHM}_{\text{HI}}(R)}\right)^2\right\} + 0.19 \cdot \exp\left\{-\left(\frac{z}{1.38 \cdot \text{FWHM}_{\text{HI}}(R)}\right)^2\right\} + 0.11 \cdot \exp\left\{-\left(\frac{|z|}{1.75 \cdot \text{FWHM}_{\text{HI}}(R)}\right)\right\} \right] \text{cm}^{-3}.$$

Here we are rescaling the width of the function according to our model of the HI gas layer thickness while the normalization factor  $k(R)$  is fixed by  $\text{CD}_{\text{HI}}(R)$ .

#### 4.3.2 Molecular hydrogen ( $\text{H}_2$ )

We model the distribution of the molecular hydrogen component in a similar way, using the azimuth-averaged results of Clemens et al. (1988) for  $\text{H}_2$  in the first Galactic quadrant. The radial distribution of the vertical molecular hydrogen CD is modeled empirically to follow the distribution provided by Clemens et al. (1988)<sup>4</sup> as

$$\text{CD}_{\text{H}_2} = (1.54 \cdot 10^{19} \text{cm}^{-2}) \cdot R^8 \exp\{-1.69 \cdot R\}.$$

For the FWHM of the  $\text{H}_2$  layer thickness as function of the

Galacto-centric radius, we use the powerlaw parameterization by Clemens et al. (1988):

$$\text{FWHM}_{\text{H}_2} = (562 \cdot R)^{0.58} \text{ pc}.$$

The density distribution perpendicular to the Galactic plane follows the shape described in Ferrière (2001), again rescaled in width and normalization  $l(R)$  as given by  $\text{CD}_{\text{H}_2}(R)$  and  $\text{FWHM}_{\text{H}_2}(R)$ ,

$$\langle n_{\text{H}_2} \rangle(R, z) = l(R) \exp\left[-4 \ln 2 \left(\frac{z}{\text{FWHM}_{\text{H}_2}(R)}\right)^2\right] \text{cm}^{-3}.$$

#### 4.3.3 Spiral Arms

As an option, we also allow for the modulation of the gas density towards Galactic spiral arms. In the inter-arm regions Clemens et al. (1988) found values of the space-averaged density of molecular hydrogen lowered by a factor of  $\sim 3.6$  compared to the density inside the arms. A similar contrast of  $\sim 4$  is found for the HI surface density, see Kulkarni (1982).

The geometrical arm model is taken from Valée (2005), but we rescaled the spirals to match our value of  $R_{\odot} = 8.5 \text{ kpc}$ , which is somewhat larger than Valée's value of 7.9 kpc. The width of the spiral arms is adopted from Russeil (2003), who found a FWHM value for all four arms of  $\langle w \rangle = 1.32 \text{ kpc}$ , corresponding to a Gaussian width of  $\sigma_w = 0.56 \text{ kpc}$ . The space-averaged gas density follows a Gaussian profile perpendicular to the spiral arm tangential direction so that the density between the arms is a factor of 4 lower than in their center,

$$\langle n_{\text{mod}} \rangle = (\langle n_{\text{HI}} \rangle + \langle n_{\text{H}_2} \rangle) \cdot s \cdot \left[ 3 \exp(-d^2/2\sigma_w^2) + 1 \right].$$

Here,  $d$  is the distance to the nearest spiral arm and  $s = 0.32$  is an empirically determined normalization factor to obtain the same number of hydrogen nuclei in both the modulated and unmodulated models.

The resulting gas densities, averaged perpendicular to the Galactic plane, are shown in Fig. 5.

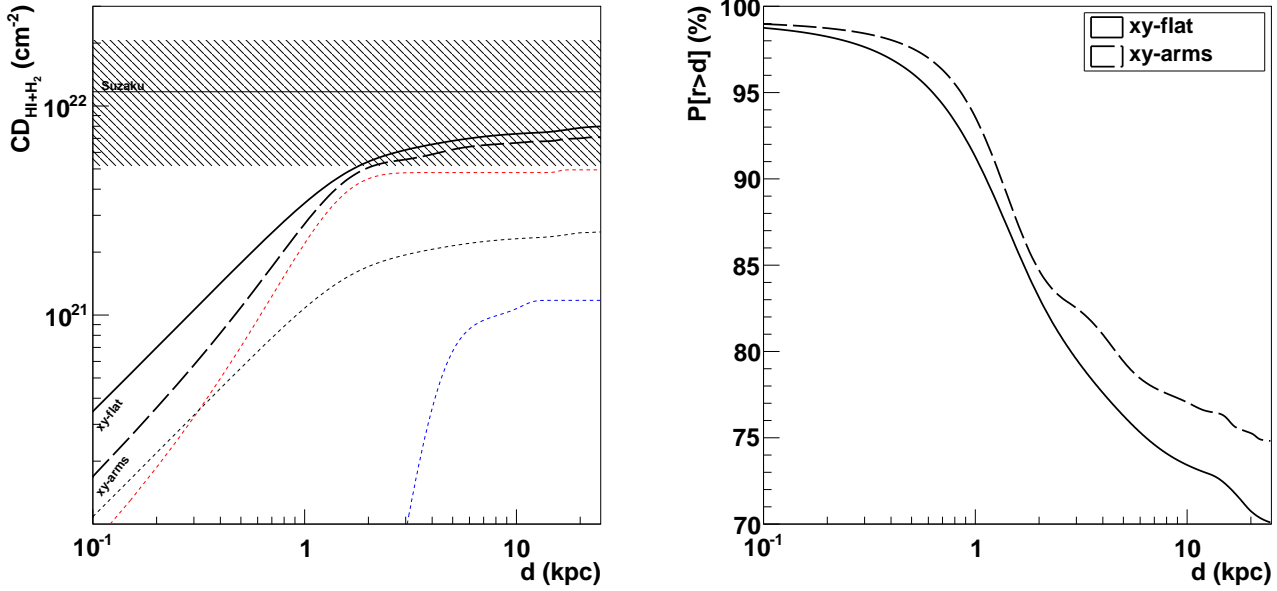
#### 4.4 The distance to HESS J1507–622

The model described in sect. 4.3 allows to derive the theoretically expected neutral hydrogen CD in the direction of CXOU J150706.0–621443 as a function of the distance to Earth,  $d$ . The result is shown in the left panel of Fig. 6. For distances larger than  $\sim 2 \text{ kpc}$ , both models agree within errors with the *Suzaku* measurement. The spiral arm modulation results in overall lower values for  $d$  than those obtained for a 'flat' galaxy in the x-y plane. This is especially pronounced at distances smaller than 1 kpc, as the main contribution to the CD stems from the gas concentrated in the Carina arm (red line in Fig. 6, see also Fig. 5).

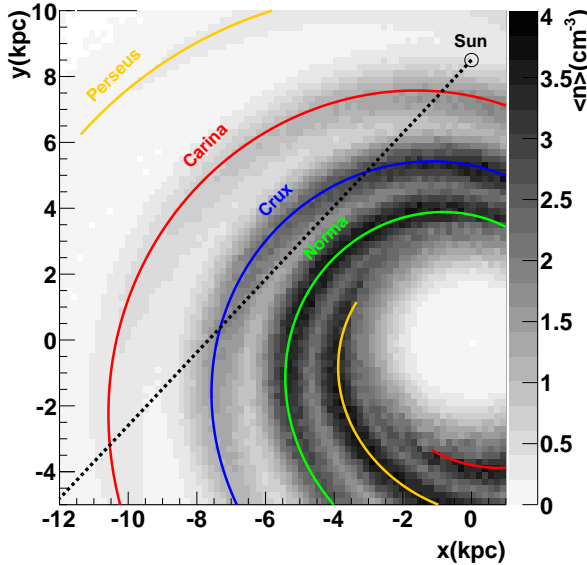
We use the modeled CD profile along  $d$  to calculate the probability  $P[r > d]$  of CXOU J150706.0–621443, and presumably HESS J1507–622, being located at a distance  $r > d$ . To that end, we treat the asymmetric error interval of the X-ray  $N_{\text{H}}$  measurement as a distorted Gaussian distribution, following Method 2 described in Barlow (2004). The resulting profile is shown in Fig. 6. As can be seen, the X-ray measurements and Galactic gas model places CXOU J150706.0–621443 with probabilities of 70% (flat galaxy) or 75% (arm-modulated) at distances larger than 25 kpc, which corresponds to the edge of the Galaxy. Interestingly, HESS J1507–622

<sup>4</sup> Rescaled to the updated value of  $R_{\odot} = 8.5 \text{ kpc}$ , see Ferrière (2001).





**Figure 6.** **Left:** Calculated CD of HI and H<sub>2</sub> gas in the direction of HESS J1507–622 as a function of the distance to Earth. The solid line shows the model expectation in the absence of any Galactic spiral arm gas modulation while the thick dashed line takes such a modulation into account. The thin dashed lines represent the contributions of the inter-arm (black) and the intra-arm gas (colored, see Fig. 5). **Right:** Probability profile as a function of the distance to Earth for CXOU J150706.0–621443 being located at a distance  $r$  greater than  $d$ .



**Figure 5.** HI + H<sub>2</sub> atomic nucleus density, averaged along the perpendicular direction to the Galactic plane. Additionally, the line of sight towards HESS J1507–622 (dashed) and the Valée spirals (colored) are shown.

is located very close to the super-galactic plane (SG-lon: 183.6°, SG-lat: 0.2°), a location where nearby Extragalactic objects cluster (Lahav et al. 2000), and also where all non-blazar Extragalactic

TeV sources are concentrated (see TeVCat<sup>5</sup>). Although interesting, these values, however, do not yet allow to make any definitive statements on the exact location of HESS J1507–622, due to the relatively large uncertainties of the  $N_{\text{H}}$  measurement from the X-ray spectrum.

Our constraints on the distance to HESS J1507–622 can be compared to the distance estimates by Matsumoto et al. (2014) for Suzaku J1508.8–6210 of  $d = 1.7 \pm 0.2$  kpc and for CXOU J150706.0–621443 of  $d = 2.6 \pm 1.7$  kpc. We note here that also their measurements of the total  $N_{\text{H}}$  are compatible with the total Galactic CD within  $1\sigma$  uncertainties, and thus the calculation of an upper bound of the distances to these two sources should not be possible, contrary to what is indicated by the symmetric distance uncertainties quoted by Matsumoto et al. (2014). In such cases, the only constraints on the distance can be given in terms of probabilities for  $d$  to be larger than a certain value  $r$ , as, e.g., derived from our model (see Fig. 6). Furthermore, the estimates by Matsumoto et al. (2014) are based on the assumption of an average Galactic ISM density of  $1 \text{ cm}^{-3}$ , which is probably not appropriate for the specific case of HESS J1507–622, due to its large offset from the Galactic plane and hence significantly lower ambient densities, particularly for large distances. This assumption of a too dense medium systematically biases the resulting distance estimates towards lower values.

We note here that the total values of  $N_{\text{H}}$  derived from the Galaxy model are comparable or slightly larger than those estimated from measurements (see sect. 4.2). Therefore, the derived probabilities of HESS J1507–622 being located at a distance  $r > d$  in this section can be viewed as conservative, since lower values of  $N_{\text{H}}$  in the model would result in even larger distances.

<sup>5</sup> <http://tevcat.uchicago.edu/>

For comparison, we apply the same procedure to Suzaku J1508.8–6210. The result can be seen in Fig. 7. Both the unmodulated and spiral arm model predictions for the absolute neutral hydrogen CD in the direction of the source agree within errors with the *Suzaku* measurements. As the predicted total hydrogen CD in case of the modulated gas model almost perfectly coincides with the X-ray value, the estimated probability for Suzaku J1508.8–6210 to be extragalactic or at the edge of the Milky Way is  $\sim 50\%$  in this case. With the unmodulated gas model, the total hydrogen CD is predicted at a higher value but still matches the upper  $1\sigma$ -limit of the X-ray measurement, favoring a Galactic nature of the source with a probability of  $\sim 84\%$ . Again, our model predictions on the total hydrogen CD are somewhat larger than the independent measurements presented in sect. 4.2, which would result in lower probabilities of Suzaku J1508.8–6210 being a Galactic source.

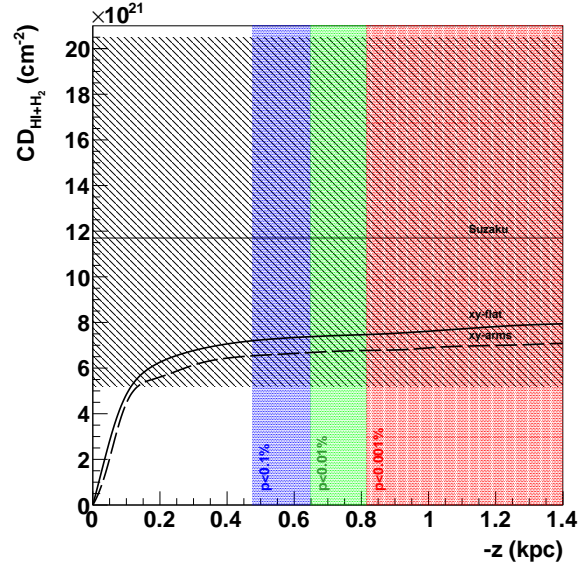
#### 4.5 Implications for a PWN scenario

As discussed in the previous section (4.4) the comparatively large value of  $N_H$  measured in X-rays might indicate a considerable line-of-sight distance of CXOU J150706.0–621443, and potentially HESS J1507–622, from Earth. Given the rather high Galactic latitude ( $b = -3.49^\circ$ ), this would also imply a large vertical distance to the Galactic plane,  $z$ . Also, the Galactic longitude ( $l = 317.97^\circ$ ) of HESS J1507–622 defines a minimal value of  $R$ ,  $R_{min} = 5.7$  kpc. These distances, together with a model for the distribution of PWNe in the Galaxy, are used in the following to estimate the probability of a PWN scenario for HESS J1507–622.

##### 4.5.1 Un-recycled pulsars

First we investigate the probability of HESS J1507–622 being the PWN associated with an un-recycled pulsar. This is the population of pulsars considered in the study of Mattana et al. (2009). We assume that PWNe follow the distribution of pulsars in the Milky Way. Corresponding radial and vertical distribution functions have been proposed by Yusifov & Küçük (2004) and Faucher-Giguère & Kaspi (2006), respectively, and are adopted in our model. The mentioned radial distribution describes a powerlaw increase followed by an exponential decay,  $\rho(R) \sim R^{1.64} \exp\{-4.01 \cdot (R - R_\odot)/R_\odot\}$ , and reaches its maximum at  $R = 3.2$  kpc. For the distribution perpendicular to the Galactic plane we assume an exponential profile with scale height  $z_0$ . The value of  $z_0$  is estimated by a fit to the  $z$ -distribution of pulsars detected by the Fermi-LAT instrument (Abdo et al. 2013, the Second *Fermi* Large Area Telescope Catalog of Gamma-Ray Pulsars), which provides a homogeneous sky coverage. To fit the pulsar distribution we used all Galactic Fermi-detected un-recycled pulsars without any cut on age or spin-down power. This results in a sample of 51 pulsars. An exponential fit to the  $z$ -distribution ( $\chi/ndf = 9.6/7$ ) yields a scale height of  $z_0 = (74.0 \pm 16.1)$  pc.

With this distribution function one can determine the probability  $\tau$  to find a pulsar at any given coordinate  $\{R > R_{min}, z(\tau)\}$ . For instance, assuming a value of  $z_0 = 74$  pc, at a perpendicular distance to the Galactic plane of  $z(0.001\%) = 815$  pc, the chance to find a pulsar is  $\tau = 0.001\%$ . We calculated the CD towards HESS J1507–622 that corresponds to  $z(0.001\%)$  and compare it to the X-ray measurement of  $N_H$ , again treating the probability distribution of the latter as a distorted Gaussian (see Sec. 4.4). This comparison places the sources with a probability of 73% (flat galaxy)



**Figure 8.** Same as in the left panel of Fig. 6, but here as a function of  $z$ . Additionally, the  $z$ -values corresponding to  $\tau = 0.1\%$ ,  $0.01\%$ ,  $0.001\%$  and assuming a vertical scale height of the pulsar distribution of  $z_0 = 74$  pc are shown.

**Table 4.** Non-PWN scenario probability as a function of  $z$ . Probabilities have been calculated for the exponential scale height of the pulsar distribution  $z_0$  of 74 pc.

$\tau$	$z(\tau)/\text{pc}$	$P_{flat}$	$P_{arms}$
0.1%	475	74%	78%
0.01%	647	73%	77%
0.001%	815	73%	76%

and 76% (spiral arms) at values  $z > z(0.001\%)$ . Thus, at a confidence of 99.999%, model and measurement exclude a PWN scenario for HESS J1507–622 with probabilities between 73% and 76%. Probabilities for different values of  $\tau$  are given in Tab. 4 and also shown in Fig. 8 for  $z_0 = 74$  pc. Again, given the relatively large uncertainties of the X-ray measurement of  $N_H$ , these results do not allow to disfavor a PWN scenario with high confidence.

##### 4.5.2 Millisecond pulsars

In this section we discuss the implication of the rather large value of  $N_H$  for the case where HESS J1507–622 is the nebula associated with a millisecond pulsar (MSP). MSPs are commonly believed to be very old pulsars with characteristic ages of  $10^9$  years that were recycled by accretion from a companion star (e.g. Alpar et al. 1982; Grégoire & Knödseder 2013). Following the discussion of the potentially old age of HESS J1507–622 in Sect. 4.1, a MSP may be a potential counterpart. Owing to their age their distribution features a large Galactic scale height of about 1 kpc and a Galactic scale length of about 4 kpc (as measured from the *Fermi*-LAT detected MSPs Grégoire & Knödseder 2013). This scale height is larger than the scale heights of cold hydrogen and therefore no constraints on the probability of HESS J1507–622 being a PWN associated to a MSP can be made. However, so far no detection of a PWN related to a MSP in VHE gamma-rays has been reported in the literature.

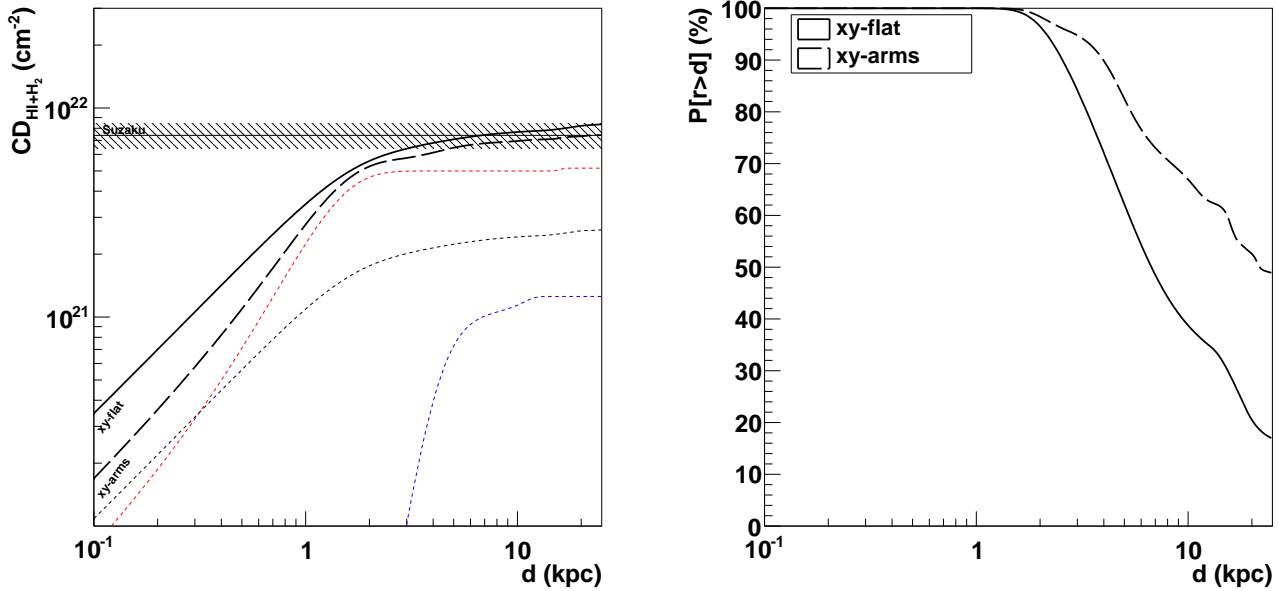


Figure 7. Same as in Fig.6, but calculated for Suzaku J1508.8–6210.

However, this can in principle be a selection bias since MSPs do not strongly cluster around the Galactic plane, the region with the deepest large-scale exposure by VHE gamma-ray telescopes such as H.E.S.S. Future observations of powerful MSPs are required to test the presence of VHE-gamma-ray emitting PWNe around these objects.

## 5 SUMMARY AND OUTLOOK

In this paper we present spectral results for the potential X-ray counterpart to the enigmatic TeV gamma-ray source HESS J1507–622. On the basis of this new measurement we provide interesting constraints on the parameters of the underlying population of relativistic particles, and also on the line-of-sight distance to the object. Even though this study represents a significant step forward in the identification of the origin of non-thermal emission from this puzzling object, the relatively low count statistics of the X-ray detection, and the resulting large uncertainties of the derived model parameters do not allow very strong conclusions. However, we see indications that the potential X-ray counterpart to HESS J1507–622 might be located at a considerable distance from Earth, which would strongly challenge established models for Galactic gamma-ray source populations, in particular PWNe.

Future deeper X-ray observation with high-throughput instruments providing higher statistical quality could greatly improve the strength and conclusiveness of this result.

## ACKNOWLEDGMENTS

This research has made use of data obtained from the Suzaku satellite, a collaborative mission between the space agencies of Japan (JAXA) and the USA (NASA). This research has made use of data and/or software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC), which is a service of the

Astrophysics Science Division at NASA/GSFC and the High Energy Astrophysics Division of the Smithsonian Astrophysical Observatory.

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